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Influence of occlusal splints on TMJ condyle-fossa relationship and disc shape

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To my grandparents

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1. Abstract

Background. Occlusal splints are nowadays commonly used in dentistry to treat symptoms of myoarthropathies of the masticatory system, but also to treat simple occlusal parafunctions. Still, the exact mechanism by which the treatment works is unknown. The aim of this study was to find out the answers to following questions: 1. is there an immediate change of the minimum condyle-fossa distance and accompanying disc thickness by inserting a Michigan splint and 2. is it possible to displace the main loading area on the disc by inserting a Michigan splint?

Methods. For each subject and each temporomandibular joint (TMJ), four magnetic resonance imaging (MRI) recordings were taken in the following situations: maximum intercuspation without/with Michigan splint, maximum protrusion without/with Michigan splint (splint 3 mm). The image stacks were reconstructed to three-dimensional virtual models using the Amira™ software. Several measurements were taken on these models and subsequently compared within and across the subjects.

Results. No significant change in the global minimum condyle-fossa distance could be achieved by inserting a Michigan splint. However, in most TMJs (18 out of 20) a shift of the main loading area (the area with the smallest joint space) could be observed. This effect could cause an unloading of the otherwise most loaded zone.

The intensities of MR images within the discs did not differ significantly intraindividually, thus indicating that all discs were segmented in the same way and were comparable.

Most subjects (8 of 10) reached a more anterior condylar position during protrusion with inserted splint compared to the situation without splint.

Conclusion. With this method, no increase of the overall minimum TMJ space due to the sole insertion of a Michigan splint could be demonstrated, however a shift of the main loading area could be shown.

2. Zusammenfassung

Hintergrund. Aufbissschienen kommen heute in der Praxis sehr häufig zur Anwendung bei der Therapie von Myoarthropathien des Kausystems, aber auch von einfachen okklusaren Parafunktionen, ohne dass der genaue Wirkungsmechanismus verstanden wird. Ziel dieser Studie war herauszufinden: 1. ob allein durch das Einsetzen einer Michiganschiene eine unmittelbar messbare Veränderung des minimalen Abstandes zwischen Kondylus und Fossa und der minimalen Diskusdicke im Kiefergelenk erreicht werden kann und 2. ob sich durch das Einsetzen einer Michiganschiene eine Verschiebung der Hauptbelastungszone des Diskus ergibt.

Methoden. Von jedem Probanden und jedem Kiefergelenk wurden vier Magnetresonanz-Aufnahmen (MRI) in folgenden Situationen gemacht: maximale Interkuspidation ohne/mit Michiganschiene, maximale Protrusion ohne/mit Michiganschiene (Schiene 3 mm). Die Aufnahmen wurden mittels der Amira™-Software zu einem dreidimensionalen Modell zusammengefügt, welches sich anschliessend vermessen und beurteilen liess. Die erhaltenen Werte wurden dann innerhalb und über alle Probanden hinweg verglichen.

Resultate. Nur mit dem Einsetzen der Michiganschiene konnte keine signifikante Veränderung der globalen Breite des Gelenkspaltes erreicht werden. Hingegen kam es in den meisten Gelenken (18 von 20) zu einer Verschiebung der meist belasteten Zone (die Zone mit dem kleinsten Gelenkspalt) und somit wahrscheinlich auch zu einer Entlastung der üblicherweise belasteten Zone.

Die Intensitäten der MRI-Bilder im Bereich der Disken wurden verglichen. Sie unterschieden sich intraindividuell nicht signifikant, was darauf hindeutet, dass die Disken alle auf gleiche Weise segmentiert wurden und vergleichbar waren.

Die meisten Probanden (8 von 10) gelangten in eine weiter anteriore Kondyluslage mit eingesetzter Schiene verglichen zur Situation ohne Schiene.

Schlussfolgerung. Mit dieser Methode liess sich beim alleinigen Einsetzen einer Michiganschiene keine Vergrösserung des Gelenksspalts nachweisen, wohl aber eine Verschiebung der Hauptbelastungszone.

3. Introduction

Myoarthropathies (MAP) of the masticatory system are disturbances in the temporomandibular joint (TMJ) and in the masticatory muscles caused by inflammatory and/or degenerative processes as well as overloading. Different diagnoses range from discopathy and tendomyopathy on to arthrosis. Most MAP patients suffer from a tendomyopathy (LeResche et al., 1991; List and Dworkin, 1996).

The history of MAP reaches as far back as to old Egypt where jaw displacements were repaired manually. The first operations on the TMJ were performed in the late 18th and early 19th century. From the 1930s to the 1950s, occlusal disharmonies were held responsible for MAP. Furthermore, in the 1950s also muscular and psychological aspects were considered (Charles Mc Neill, 1997). From today's point of view, multifactorial causes are held responsible for MAP development. On one hand, mechanical overloading, macro- and micro-traumas or previous dental therapies are considered, on the other hand, dental, occlusal or anatomical, but also psychological and behavioral factors, such as bruxism are being studied. Furthermore, hormonal influences are discussed: female sex hormones (estrogen and prolactin) might adversely affect the adaptive capacity of TMJ articular tissues by inhibiting fibro-cartilage synthesis and enhancing extracellular matrix degradation (Milam et al., 1995).

The overall cause of MAPs lies possibly in the combination of components of biomechanical, occlusal, psychological and psychosocial origin and becomes symptomatic when the adaptability of the TMJ structures is exceeded. In addition, Gallo et al. (2005) have found that the incongruity of the articular TMJ surfaces load the fibrocartilaginous articular disc mostly in mediolateral direction, in which the disc is weaker. Its dislocation and failure seem to be closely related to the development of TMJ osteoarthritis. A closer look at the mechanical aspects of the TMJ shows that both TMJs are loaded during chewing, the balancing more than the working joint, the intra-articular distance being smaller on the balancing than on the working side but also for hard than for soft food, on closing than on opening (Gallo et al., 2005).

Signs and symptoms of MAP are common. Pain in the TMJ area, jaw clicking, muscle fatigue, headaches, but also toothaches range among the symptoms. The highest prevalence of MAP is found between age 18 and 45 (Schiffman and Fricton, 1988; Wänman, 1987). Clinically significant symptoms arise with a prevalence of 5% (Goulet et al., 1995), 3-7% of the symptomatic patients need a treatment (De Kanter et al., 1992; Schiffman and Fricton, 1988; Solberg et al., 1979). MAP can lead to a disruption of daily activities and impair social and personal functioning.

Due to MAP multifactoriality, a psychosocial anamnesis always belongs to clinical dental assessment besides a specific subjective description, e.g. by means of a VAS (visual analogous scale), and a general anamnesis. The clinical investigation with palpation of the musculature and joints as well as a functional analysis belong to the dental appraisal of a MAP patient. Still, a pathology-specific diagnosis is in most cases impossible. That is why various therapy attempts have been made for MAP treatment. These attempts include medication, psychotherapy, physiotherapy, cognitive behavioral therapy, splint therapy, muscle-relaxing appliances, low level laser therapy (Fikackova et al., 2006) and in rare cases also surgery. A therapy is mainly possible only symptomatically, however, there is often a spontaneous remission or even healing observed. Sometimes, the situation can also be improved by detailed information and instructions given by the dentist.

Most often a splint therapy is used for MAP treatment, as a survey among German dentists has shown. Ommerborn et al. (2011) report that occlusal splints were by far the most frequently prescribed therapy for bruxism management, followed by relaxation techniques, occlusal equilibration, physiotherapy, and prosthodonic reconstruction. The occlusal stabilization splint with canine guidance was the splint type most often prescribed. These findings should also apply to Switzerland. However, it seems to make no big difference which kind of splint is used, be it a stabilization splint, a prefabricated splint or a NTI (nociceptiv trigeminal inhibition) splint. All types of splints lead to an improvement of MAP symptoms (Harada et al., 2006; Jokstad et al. 2005; Nilner et al., 2008; Stapelmann et Türp, 2008). Moreover, a reduction of nocturnal parafunction could also be detected while wearing the splint (Clark et al., 1979; Glaros et al., 2007; Pierce and Gale, 1988) and stabilization splints seem to have a positive effect on pain severity caused by MAP (Al-Ani et al., 2005; Ekberg et al., 2002; Ekberg et al., 1998; Forssell and Kalso, 2004; Jokstad et al., 2005; Kreiner et al., 2001; Kuttila et al., 2002; Nilner et al., 2008; Proff et al., 2007).

The mechanism of action of the stabilization splint nevertheless remains unclear. Various theories about condyle and/or disc repositioning, reduction of the electromyographic activity of the masticatory muscles, modification of the oral behavior pattern or change in occlusion could not be confirmed. It is therefore advisable to use the splint only for a habit management aid or in order to provide protection against dental damage (Dao and Lavigne, 1998). There is insufficient evidence for or against a better effectiveness of stabilization splint therapy over other methods for MAP treatment (Al-Ani et al., 2005; Nilner et al., 2004; Shibuya et al., 2007; Türp et al., 2004). A successful outcome develops most likely from a combination of spontaneous remission, an interaction between patient and dentist (information), a placebo effect, and milieu changes as well as cognitive awareness. Finally, splint therapy is still better than no therapy at all (Wright et al., 1995).

There are also negative effects when using a splint. These can range from tooth decay, gingivitis, phonetic and aesthetic losses, to occlusal changes. It has also been reported that splint therapy seems to modify peripheral information at the level of the Central Nervous System, leading to modifications in corporal postural tone (Magdaleno and Ginestal, 2010).

In this dissertation, a Michigan type of splint has been used because this is the most common one and because this type of splint has also been studied in earlier dissertations (Mang H, 2006 and Vlcek D, 2011). The Michigan splint is believed to bring the mandible back to a physiological condyle-fossa-relationship by a self-repositioning process. It has therefore a flat and smooth design and it creates a temporary and removable ideal occlusion. In Mang's dissertation, an increase of global TMJ space for habitual closure, protrusion and contralateral laterotrusion was found. A change in the topographical condyle-fossa relationship, and therefore a new distribution of contact areas between joint surfaces was also shown (Ettlin et al., 2008). Also Vlcek found that effortless closing on a 3 mm splint resulted in an increased intraarticular space compared to a no-splint condition. Yet, when clenching on the splint, the condyle was shifted cranially and ventrally with a resultant narrowing of the joint space (Vlcek 2011). However, Kuboki et al. (1999) used a method based on computer tomography in subjects with anterior disc displacement without reduction and measured directly the condyle-fossa relationship under different conditions. They came to the conclusion that upon comfortable closure and maximum clenching – with the use of stabilization appliances and mandibular anterior repositioning appliances – the joint space was not significantly different from that seen in maximum intercuspation. These findings suggest that these appliances do not induce an increase in joint space during closing and clenching in joints with anterior disc displacement without reduction.

4. Study Question

The aim of the present dissertation was to use MRI recordings directly under different splint wearing conditions and state-of-the-art computer graphic technology in order to ascertain whether condyle-fossa relationship and disc shape are influenced by inserting a 3 mm Michigan splint.

5. Materials and Methods

5.1. Subjects

Ten healthy asymptomatic volunteers (six females and four males) of age ranging from 23 to 40 years participated in the study (Table 1). All volunteers were selected according to standard criteria (Vlcek, 2011), informed about the dissertation contents, and gave their informed consent. Both their TMJs were asymptomatic and there were no contraindications for their participation, neither for Michigan splint fabrication nor for MRI scans. The study protocol was approved by the local ethics committee.

5.2. Data acquisition

Bilateral TMJ MRI scans of each subject were produced in four different situations: i.e. maximum intercuspation without and with splint and maximum protrusion without and with splint. These images, reconstructed three-dimensionally with the Amira™ software, yielded models of these four situations for both TMJs of each subject which were finally compared to each other.

5.2.1. Michigan splint

A commonly used Michigan splint with canine guidance was produced as follows:

Two alginate impressions of the upper and lower jaw and a silicone index (Jet bite, Coltène/Whaledent Inc., 235 Ascot Pkwy., OH 44223) were taken from each test person. The impressions were poured with a high strength dental stone. The lower cast was mounted arbitrarily in a Gerber articulator (Condylator Service, CH-8038 Zürich), the upper cast was then adapted with the silicone index in maximum intercuspation to the lower cast. As in Mang’s dissertation (2008), the vertical dimension of the articulator was opened until a clearance of slightly more than 3 mm between the mesial marginal ridge of the first molar and the opposing occlusal surfaces was reached. On the upper jaw model the common dental equator was determined and marked by means of a parallelometer. The splint edges were constructed in the side tooth area approximately 1-2 mm above the equator, in the front tooth area approximately 1 mm cranially to the incisal ridge. The edges of the splint reached at most 1 mm from the gingival margin. All recessed buccal and palatinal areas as

well as the occlusal fissures were blocked out with plaster. Then the upper splint was fabricated in wax and the canine guidance surfaces were waxed. As soon as the occlusion of the wax splint had one occlusal contact per antagonist and one could measure 3 mm between the mesial marginal ridge of the first molar and the opposing occlusal surfaces, the splint was embedded in a muffle and then stuffed with hard clear acrylat plastic, a cold-cure resin (Candulor Aesthetic, Candulor AG, CH-8602 Wangen bei Dübendorf). Afterwards, the finished Michigan splint was tested in the subject’s mouth and was grinded off until following conditions were fulfilled: one contact point per antagonist, freedom in centric, and canine guidance in protrusion and laterotrusion in order to produce an occlusal clearance in the molar region of approximately 1 mm. In order to confirm the desired thickness, a small hole was drilled in the splint at the mesial marginal ridge of the first molar and verification measurements were performed, the same way as in Mang’s thesis.
Furthermore, an intraoral silicone index (Jet bite, Coltène/Whaledent Inc. 235 Ascot Pkwy., OH 44223) was made in order to block the teeth in position thus assuring a steady location of the mandible in protrusion during MR imaging (Figure 5).

5.2.2. MR imaging

MRI is the best way to display the TMJ articular disc (Carr et al., 1987; Katzberg et al., 1985; Liedberg et al., 1996; Rao 1995). Besides, there are no ethical objections to record healthy temporomandibular joints by means of MRI, because this technology works without ionizing radiation. Furthermore, MRI is also possible in spite of metallic reconstructions and fixed appliances. In this study, imaging was performed bilaterally in a 1.5 T machine by means of proton density protocols. One scan lasted 270 s and produced 28 2 mm thick slices on each side. The test persons were instructed to hold the teeth together with light pressure. The first scan occurred in maximum intercuspation, the second one in protrusion. After inserting the 3 mm thick occlusal splint the procedure was repeated.

5.2.3. Amira™ software

The Amira™ program (Visage Imaging GmbH, Lepsiusstrasse 70, 12163 Berlin/Germany) allows the user to visualize and reconstruct MRI scans in a three-dimensional model. This happens by manual marking of the anatomical structures of the TMJ slice by slice: this process is called segmentation. Each segmented slice is merged by Amira™ to a three-dimensional model which can be used for further processing. In this case, Amira™ was used to calculate the minimum condyle-fossa distance, disc thickness, the main loading areas in the TMJ in maximum intercuspation and protrusion, the mean MR intensity of the disc and condylar advancement in protrusion.

5.3. Data analysis

5.3.1. Minimum condyle-fossa distance

The three-dimensional models of condyle and fossa were considered only in the areas where the disc was present in order to determine the main loading zone, i.e. the zone with minimum condyle-fossa distance. Amira™ laid a finely meshed net over both bone structures, connected the grid points between them and then calculated the distances between condyle and fossa for each possible position. This distance measurement was always performed bilaterally, once with the condyle and once with the fossa as a reference. The distances were summarized in a histogram and their values were transferred to an Excel™ spreadsheet in order to calculate the overall smallest distance and the thirty smallest distance values.

5.3.2. Minimum disc thickness

For disc thickness calculation, it was necessary first to define a fossa-close and a condyle-close disc surface. Also here Amira™ spanned a finely meshed net over both surfaces and calculated the distances once from the fossa-close to the condyle-close surface and once from the condyle-close to the fossa-close surface. Again, the values were transferred to an Excel™ spreadsheet and the overall smallest distance and the thirty smallest distance values were calculated.

5.3.3. Disc-related stress-fields in maximum intercuspation and protrusion

The main loading area appeared color-coded in Amira™ (Figure 9). Its position was defined qualitatively in a 3×3 matrix in caudodorsal view (Table 9). Then, the shift of the main loading area from the situation without splint to that with splint was shown by means of a vector listed in an Excel™ table.

5.3.4 Condyle-related stress-fields in protrusion

The main loading area appeared color-coded also on the condyle in Amira™ as already done for the disc. The condyle was qualitatively assessed from a frontocranial view in a 3×3 matrix where the main loading area was marked (Table 9). Again, the shift of the main loading area from the situation without splint to that with splint was represented with a vector and listed in Excel™.

5.3.5. Mean intensity of the disc in MRI scans

In order to prove similar segmentation criteria for all conditions (i.e., on both sides, without and with splint, in maximum intercuspation and in protrusion) Amira™ calculated the mean intensity of the disc over all MRI scans. The values were then tabulated in Excel™.

5.3.6. Condylar advancement in protrusion

To compare condylar advancement in protrusion without and with splint, the distance between the most caudal point of the fossa and the most cranial point of the condyle was measured in Amira™ and tabulated in Excel™.

5.4. Statistical analysis

All statistical evaluations were performed by means of analysis of variance for repeated measurements in the statistical program SPSS™ (IBM Corporation, Armonk, NY 10504-1722). Statistical significance was set at a level of $p<0.05$.

6. Results

6.1. Minimum condyle-fossa distance

The insertion of a 3 mm Michigan splint led to no significant change of the minimum distance between condyle and fossa in maximum intercuspation as well as in protrusion ($p<0.103$). The results are shown in Tables 2 – 6 as well as in Figures 6 and 7.

Following values refer always to the average of the thirty smallest distances:

- The values of the minimum condyle-fossa distances **without** splint in *maximum intercuspation* ranged from 0.5 to 1.7 mm with a median of 1.0 mm on the left and ranged from 0.8 to 1.4 mm with a median of 1.2 mm on the right.
- The minimum condyle-fossa distances **with** splint in *maximum intercuspation* ranged from 0.3 to 1.6 mm with a median of 1.2 mm on the left and ranged from 0.8 to 1.4 mm with a median of 1.1 mm on the right. Therefore, the **difference** between the situation without splint and that with splint ranged from -0.3 to 0.2 mm with a median of -0.1 mm on the left and from -0.4 to 0.3 mm with a median of -0.1 mm on the right.
- The minimum condyle-fossa distances **without** splint in *protrusion* ranged from 0.5 to 1.2 mm with a median of 0.9 mm on the left and ranged from 0.5 to 1.3 mm with a median of 0.9 mm on the right.
- The minimum condyle-fossa distances **with** splint in *protrusion* ranged from 0.6 to 1.3 mm with a median of 0.9 mm on the left and ranged from 0.2 to 0.9 mm with a median of 0.8 mm on the right. Therefore, the **difference** between the situation without splint and that with splint ranged from -0.3 to 0.3 mm with a median of -0.1 mm on the left and from -0.6 to 0.2 mm with a median of -0.1 mm on the right.

In summary, in maximum intercuspation, there was a minimal increase of the minimum distance in 5 TMJs, whereas in 13 TMJs the distance decreased slightly and in 2 TMJs there was no change. Similarly, in protrusion, in 5 TMJs the distance increased minimally, in 12 TMJs there was a slight decrease and in 3 TMJs no change could be found.

6.2. Minimum disc thickness

The insertion of a 3 mm Michigan splint led to no significant change of the minimum disc thickness neither in maximum intercuspation nor in protrusion ($p < 0.103$). The results are shown in Tables 2 – 6 as well as in Figures 6 and 7.

Following values refer always to the average of the thirty smallest distances:

- The values of the minimum disc thickness **without** splint in *maximum intercuspation* ranged from 0.0 to 1.5 mm with a median of 1.0 mm on the left and ranged from 0.6 to 1.2 mm with a median of 0.9 mm on the right.
- The minimum disc thickness **with** splint in *maximum intercuspation* ranged from 0.0 to 1.3 mm with a median of 0.9 mm on the left and ranged from 0.4 to 1.2 mm with a median of 0.9 mm on the right. Therefore, the **difference** between the situation without splint and that with splint ranged from -0.2 to 0.2 mm with a median of -0.1 mm on the left and from -0.6 to 0.2 mm with a median of 0.0 mm on the right.
- The minimum disc thickness **without** splint in *protrusion* ranged from 0.4 to 1.1 mm with a median of 0.8 mm on the left and ranged from 0.0 to 1.1 mm with a median of 0.8 mm on the right.
- The minimum disc thickness **with** splint in *protrusion* ranged from 0.4 to 1.1 mm with a median of 0.8 mm on the left and ranged from 0.0 to 0.8 mm with a median of 0.7 mm on the right. Therefore, the **difference** between the situation without splint and that with splint ranged from -0.2 to 0.3 mm with a median of -0.1 mm on the left and from -0.6 to 0.8 mm with a median of -0.1 mm on the right.

In summary, in maximum intercuspation there was a minimal increase of the minimum distance in 7 TMJs, in 9 TMJs the minimum distance decreased slightly and in 4 TMJs there was no change. Similarly, in protrusion in 5 TMJs the distance increased minimally, in 13 TMJs there was a slight decrease and in 2 TMJs no change could be found.

6.3. Disc-related stress-fields in maximum intercuspation and protrusion

Results are summarized in Tables 7, 7a, 8 and 8a as well as in Figure 8 and were as follows: The position of the main loading area lay mainly in the central, medial or lateral zones of the disc. In the dorsal and ventral zones there was no tendency to find any main loading area. The shift vector between the situations with and without splint on the *left side*, showed tendentially a displacement to the lateral, medial or ventral side, very rarely a displacement in dorsal direction. The *right side* behaved similarly but more dorsal displacements were found.

6.4. Condyle-related stress-fields in protrusion

Results are summarized in Tables 10 and 11, as well as in Figures 9 and 10. On the *left side*, following effects were noticed: The position of the main loading area in protrusion lay mainly in the dorsal zone of the condyle, the splint being inserted or not. A tendential displacement of the main loading area could be observed in medial (6×) and in dorsal direction (7×) when the splint was inserted. Also on the *right side* the main loading area lay in protrusion mainly in the dorsal zone of the condyle. On this side however, no homogeneous directional trend of the displacement vector could be found. Indeed, the displacement occurred 4 times in medial, 3 times in lateral and 3 times in dorsal direction.

6.5. Mean intensity of the disc in MRI scans

Results are summarized in Tables 12 and 13. No significant difference could be found in disc intensity in MRI scans, neither depending on side ($p<0.189$), nor on position ($p<0.502$) nor on splint insertion ($p<0.418$).

6.6. Condylar advancement in protrusion

Results are summarized in Tables 14, 14a and 15, as well as in Figure 11. In protrusion, the insertion of a Michigan splint led to a highly significant decrease of the distance between the most caudal point of the fossa and the most cranial point of the condyle ($p<0.001$). The average decrease for the *left joints* amounted to 2.66 mm, and for the *right joints* to 2.87 mm. This means that the subjects were able to push their mandible further forwards by an average of 2.66 mm on the left and of 2.87 mm on the right side when wearing the splint. In detail, the difference of the distances ranged on the *left* between -0.05 and 4.88 mm with a median of 2.66 mm. On the *right*, the difference of the distances ranged between -0.21 and 5.64 mm with a median of 3.04 mm.

7. Discussion

In this work, changes in TMJ joint space and disc thickness and relative positions of condyle and fossa were analyzed in asymptomatic subjects without and with an occlusal appliance for maximum intercuspation and protrusion. Differently than in the theses by Mang (2008) and Vlcek (2011), the relative arrangement of the bony structures was not determined by means of dynamic stereometry (Gallo, 2005) but it was measured directly from the different recordings under different conditions taken in the MR tomograph. For this purpose, condyles and fossae were segmented several times for the same joint in different positions by means of a state-of-the-art image processing software (Amira™) that yields three-dimensional anatomical reconstructions based on a stack of sections. In order to check for a reproducible segmentation of TMJ discs, we considered the intensity values of these segmented structures: on average, they did not vary across all recordings, thus indicating indirectly that at least these anatomical components did not consist of heterogeneous material.

7.1. Minimum condyle-fossa distance and minimum disc thickness

In the present study, neither a statistically significant increase nor a decrease of the minimum condyle-fossa distance and of the minimum disc thickness could be shown while using a Michigan splint, regardless of mandibular position, neither in maximum intercuspation nor in protrusion. Changes in global minimum joint space as well as minimum disc thickness after insertion of a Michigan splint found in the work by Mang (2008) and Vlcek (2011) were explained by the incomplete closure that led to a slight mouth opening with subsequent rotation and translation when wearing the appliance. In this work, the insertion of a Michigan splint had no statistical effect on the joint space, which could be explained by the different experimental conditions and data processing with regard to previous work. In particular 1) the segmentation was repeated four times on four different datasets depicting the same joint, thus adding an uncertainty to the bony borders due to the different recordings and to the different segmentations, 2) segmentation as well as measurements were performed by means of a different software than the one used in the previous studies, thus yielding different wireframe approximations of the bony surfaces, 3) calculations of joint space and disc thickness might be based on different algorithms than in previous work, so that small changes would not be detected, given also the large interindividual variability of morphology and movement patterns.

A shortcoming of this study was indeed the lack of electromyographic or occlusal force recordings, due to the fact that the subjects were lying in the MR tomograph and were not easily accessible by measuring devices whose use in the MR environment is anyway difficult if not impossible. Consequently, the teeth were held together in every position with inter- and intraindividuell uncontrolled bite forces that might have contributed to blur the findings. Furthermore, since the subjects pushed their mandible further forwards (see 6.6) with the splint inserted, the situations without splint and with splint in protrusion were no longer comparable. Finally, all subjects had asymptomatic TMJs, this is why the present results cannot be generalized e.g. for patients with anterior disc displacement. This study however shows for the first time in our research line that segmentation of bony structures and of the disc for different condylar positions yield consistent results, as better illustrated below.

7.2. Disc-related stress-fields in maximum intercuspation and protrusion

No statistically significant changes of the minimum TMJ disc thickness could be demonstrated when wearing a Michigan splint. However, a shift of a few millimeters of the main loading area in 18 of 20 TMJs was evident, which could lead to another distribution of the mechanical loading patterns. These results are similar to the findings by Mang (2008) and Vlcek (2011) and can be explained by the peculiar anatomy of the TMJ. Indeed, the ventral fossa slope is curved as a segment of an ellipsoid with the longest axis oblique in medio-lateral direction and the condyle and fossa surfaces are incongruent. Thus, the condyle could approach the fossa more closely in the lateral or in the medial areas of the disc – depending on condylar shape and orientation – as soon as the mouth is even slightly opened and rotated. In this way, some disc areas would be unloaded and other disc areas would be compressed.

Again, this study shows that a shift in disc loading patterns when wearing an occlusal appliance can be demonstrated by segmenting the disc in different condylar positions. It can be inferred that disc loading patterns are shifted also indirectly by considering the relationship between the bony surfaces as done in previous work (Ettlin et al. 2008).

7.3. Condyle-related stress-fields in protrusion

For recordings in mandibular protrusion, a displacement of the main loading areas was found mainly in medial and dorsal direction in left side TMJs. On the right side however, the displacement pattern was slightly less clear. The dorsal displacement of the main loading area can be explained again by TMJ anatomical features. The further the condyle glides forward in protrusion, the closer its cranial zones move with respect to the fossa.

The vast majority of the subjects assumed a further anterior position in protrusion with inserted splint than they did without wearing one. During this movement, the main loading area of the condyle moved more and more to a dorsal position. Again, as mentioned in 7.2, the fossa shape is possibly responsible for the medial and lateral displacement of the main loading area when translating the mandible in ventral direction. In all subjects, the distance between condyle and fossa decreased more strongly either medially or laterally with increasing protrusion (see an example in Figure 10).

7.4. Condylar advancement in protrusion

Surprisingly, the insertion of a Michigan splint allowed asymptomatic subjects to push their mandible anteriorly in a more advanced position relative to the situation without a splint. This could be explained by considering muscle and ligament fibers of the TMJ, especially in the rear parts of the temporal muscle. Without oral appliance, the condyle is held in position by these fibers. After splint insertion however, the resulting mandibular rotation and translation as demonstrated by Mang (2008) could unload these muscle and ligament fibers, thus allowing condylar gliding in a more anteriorly advanced position. This effect would also possibly explain why some patients do not react as desired to splint therapy and still experience an increasing – rather than decreasing – TMJ loading when wearing a Michigan splint.

In conclusion, by taking MRI recordings directly under different splint wearing conditions and state-of-the-art computer graphic technology, no change of the global minimum joint space and disc thickness could be demonstrated when wearing a 3 mm Michigan splint in maximum intercuspation as well as in protrusion. However, under these conditions, the condyle-related and disc-related maximum loading areas were shifted mostly mediolaterally or dorsally resp. ventrally. Furthermore, the use of a Michigan splint appeared to allow a more pronounced condylar advancement in protrusion.

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9. Tables

Table 1. Demographic data of subjects.

Subject	Initials	Sex	Age
1	BB	female	27
2	CvZ	female	22
3	DP	female	35
4	EV	female	27
5	IV	female	27
6	KT	female	27
7	UH	male	24
8	MS	male	33
9	SK	male	26
10	RDD	male	39

Table 2. Minimum intraarticular distances in maximum intercuspation (MI) on the left side without and with the 3 mm splint and differences. The disc thickness and the condyle-fossa distance are reported individually. X0.25 and X0.75: 25th and 75th percentiles. These abbreviations are used also for tables 3 – 5.

Subject		**Disc MI left**			**Condyle/Fossa MI left**		
		without splint mm	with splint mm	Δ without splint/ with splint mm	without splint mm	with splint mm	Δ without splint/ with splint mm
1	Smallest value [mm]	0.8	1.0	0.2	1.0	1.2	0.2
	ø 30 smallest values [mm]	0.9	1.0	0.1	1.0	1.2	0.2
2	Smallest value [mm]	1.0	1.1	0.1	1.0	1.1	0.1
	ø 30 smallest values [mm]	1.0	1.1	0.1	1.0	1.1	0.1
3	Smallest value [mm]	1.0	0.8	-0.2	1.2	1.1	-0.1
	ø 30 smallest values [mm]	1.1	1.0	-0.1	1.3	1.2	-0.1
4	Smallest value [mm]	0.7	0.5	-0.2	0.9	1.1	0.2
	ø 30 smallest values [mm]	0.7	0.6	-0.1	1.0	1.2	0.2
5	Smallest value [mm]	0.0	0.0	0.0	0.5	0.3	-0.2
	ø 30 smallest values [mm]	0.0	0.0	0.0	0.5	0.4	-0.1
6	Smallest value [mm]	0.5	0.3	-0.2	1.6	1.6	0.0
	ø 30 smallest values [mm]	0.7	0.4	-0.3	1.7	1.6	-0.1
7	Smallest value [mm]	1.1	1.0	-0.1	1.3	1.2	-0.1
	ø 30 smallest values [mm]	1.1	1.1	0.0	1.3	1.2	-0.1
8	Smallest value [mm]	0.3	0.5	0.2	0.6	0.7	0.1
	ø 30 smallest values [mm]	0.4	0.6	0.2	0.7	0.7	0.0
9	Smallest value [mm]	1.5	1.3	-0.2	1.6	1.3	-0.3
	ø 30 smallest values [mm]	1.5	1.3	-0.2	1.6	1.3	-0.3
10	Smallest value [mm]	0.9	0.7	-0.2	1.0	0.7	-0.3
	ø 30 smallest values [mm]	1.0	0.8	-0.2	1.0	0.8	-0.2
	Min Smallest value [mm]	0.0	0.0	-0.2	0.5	0.3	-0.3
	Min ø 30 smallest values [mm]	0.0	0.0	-0.3	0.5	0.4	-0.3
	X0.25 Smallest value [mm]	0.5	0.5	-0.2	0.9	0.7	-0.2
	X0.25 ø 30 smallest values [mm]	0.7	0.6	-0.2	1.0	0.8	-0.1
	Median Smallest value [mm]	0.9	0.8	-0.2	1.0	1.1	-0.1
	Median ø 30 smallest values [mm]	1.0	0.9	-0.1	1.0	1.2	-0.1
	X0.75 Smallest value [mm]	1.0	1.0	0.1	1.3	1.2	0.1
	X0.75 ø 30 smallest values [mm]	1.1	1.1	0.1	1.3	1.2	0.1
	Max Smallest value [mm]	1.5	1.3	0.2	1.6	1.6	0.2
	Max ø 30 smallest values [mm]	1.5	1.3	0.2	1.7	1.6	0.2

Table 3. Minimum intraarticular distances in maximum protrusion (Prot) on the left side without and with the 3 mm splint and differences. The disc thickness and the condyle-fossa distance are reported individually.

Subject		Disc Prot left			Condyle/Fossa Prot left		
		without splint mm	with splint mm	∆ without splint/ with splint mm	without splint mm	with splint mm	∆ without splint/ with splint mm
1	Smallest value [mm]	0.8	0.9	0.1	0.9	1.3	0.4
	ø 30 smallest values [mm]	0.9	1.0	0.1	1.0	1.3	0.3
2	Smallest value [mm]	0.7	0.6	-0.1	0.7	0.6	-0.1
	ø 30 smallest values [mm]	0.8	0.7	-0.1	0.8	0.7	-0.1
3	Smallest value [mm]	1.1	0.8	-0.3	1.1	0.8	-0.3
	ø 30 smallest values [mm]	1.1	0.8	-0.3	1.2	0.9	-0.3
4	Smallest value [mm]	0.4	0.7	0.3	0.5	0.7	0.2
	ø 30 smallest values [mm]	0.5	0.7	0.2	0.6	0.7	0.1
5	Smallest value [mm]	1.0	0.9	-0.1	1.1	0.9	-0.2
	ø 30 smallest values [mm]	1.1	0.9	-0.2	1.1	0.9	-0.2
6	Smallest value [mm]	0.7	0.4	-0.3	0.9	0.7	-0.2
	ø 30 smallest values [mm]	0.8	0.5	-0.3	0.9	0.7	-0.2
7	Smallest value [mm]	0.6	1.0	0.4	1.0	1.2	0.2
	ø 30 smallest values [mm]	0.8	1.1	0.3	1.0	1.2	0.2
8	Smallest value [mm]	0.6	0.6	0.0	0.6	0.6	0.0
	ø 30 smallest values [mm]	0.7	0.6	-0.1	0.7	0.6	-0.1
9	Smallest value [mm]	0.9	0.7	-0.2	0.9	0.7	-0.2
	ø 30 smallest values [mm]	0.9	0.8	-0.1	0.9	0.8	-0.1
10	Smallest value [mm]	0.7	0.8	0.1	0.7	1.0	0.3
	ø 30 smallest values [mm]	0.7	0.8	0.1	0.8	1.0	0.2
	Min Smallest value [mm]	0.4	0.4	-0.2	0.5	0.6	-0.3
	Min ø 30 smallest values [mm]	0.5	0.5	-0.3	0.6	0.6	-0.3
	X0.25 Smallest value [mm]	0.6	0.6	-0.2	0.7	0.7	-0.2
	X0.25 ø 30 smallest values [mm]	0.7	0.7	-0.2	0.8	0.7	-0.2
	Median Smallest value [mm]	0.7	0.8	0.0	0.9	0.8	0.0
	Median ø 30 smallest values [mm]	0.8	0.8	-0.1	0.9	0.9	-0.1
	X0.75 Smallest value [mm]	0.9	0.9	0.1	1.0	1.0	0.2
	X0.75 ø 30 smallest values [mm]	0.9	0.9	0.1	1.0	1.0	0.2
	Max Smallest value [mm]	1.1	1.0	0.4	1.1	1.3	0.4
	Max ø 30 smallest values [mm]	1.1	1.1	0.3	1.2	1.3	0.3

Table 4. Minimum intraarticular distances in maximum intercuspation (MI) on the right side without and with the 3 mm splint and differences. The disc thickness and the condyle-fossa distance are reported individually.

Subject		**Disc MI right**			**Condyle/Fossa MI right**		
		without splint mm	with splint mm	Δ without splint/ with splint mm	without splint mm	with splint mm	Δ without splint/ with splint mm
1	Smallest value [mm]	0.6	0.9	0.3	1.2	1.1	-0.1
	ø 30 smallest values [mm]	0.7	0.9	0.2	1.2	1.1	-0.1
2	Smallest value [mm]	1.0	0.9	-0.1	1.3	0.9	-0.4
	ø 30 smallest values [mm]	1.1	0.9	-0.2	1.3	0.9	-0.4
3	Smallest value [mm]	1.1	0.8	-0.3	1.4	1.1	-0.3
	ø 30 smallest values [mm]	1.2	0.9	-0.3	1.4	1.2	-0.2
4	Smallest value [mm]	0.8	0.9	0.1	1.3	1.4	0.1
	ø 30 smallest values [mm]	0.8	0.9	0.1	1.3	1.4	0.1
5	Smallest value [mm]	1.2	1.2	0.0	1.2	1.2	0.0
	ø 30 smallest values [mm]	1.2	1.2	0.0	1.2	1.2	0.0
6	Smallest value [mm]	1.0	0.4	-0.6	1.2	1.0	-0.2
	ø 30 smallest values [mm]	1.0	0.5	-0.5	1.3	1.0	-0.3
7	Smallest value [mm]	0.7	0.8	0.1	1.0	0.9	-0.1
	ø 30 smallest values [mm]	0.8	0.8	0.0	1.1	0.9	-0.2
8	Smallest value [mm]	0.6	0.7	0.1	0.8	1.1	0.3
	ø 30 smallest values [mm]	0.7	0.8	0.1	0.8	1.1	0.3
9	Smallest value [mm]	0.9	0.8	-0.1	0.9	0.8	-0.1
	ø 30 smallest values [mm]	1.0	0.9	-0.1	1.0	0.9	-0.1
10	Smallest value [mm]	0.8	1.0	0.2	1.2	1.0	-0.2
	ø 30 smallest values [mm]	0.8	1.0	0.2	1.2	1.0	-0.2
	Min Smallest value [mm]	0.6	0.4	-0.6	0.8	0.8	-0.4
	Min ø 30 smallest values [mm]	0.7	0.5	-0.5	0.8	0.9	-0.4
	X0.25 Smallest value [mm]	0.7	0.8	-0.1	1.0	0.9	-0.2
	X0.25 ø 30 smallest values [mm]	0.8	0.8	-0.2	1.1	0.9	-0.2
	Median Smallest value [mm]	0.9	0.9	0.0	1.2	1.1	-0.1
	Median ø 30 smallest values [mm]	0.9	0.9	0.0	1.2	1.1	-0.1
	X0.75 Smallest value [mm]	1.0	0.9	0.1	1.3	1.1	0.0
	X0.75 ø 30 smallest values [mm]	1.1	0.9	0.1	1.3	1.2	0.0
	Max Smallest value [mm]	1.2	1.2	0.3	1.4	1.4	0.3
	Max ø 30 smallest values [mm]	1.2	1.2	0.2	1.4	1.4	0.3

Table 5. Minimum intraarticular distances in maximum protrusion (Prot) on the right side without and with the 3 mm splint and differences. The disc thickness and the condyle-fossa distance are reported individually.

Subject		Disc Prot right			Condyle/Fossa Prot right		
		without splint mm	with splint mm	Δ without splint/ with splint mm	without splint mm	with splint mm	Δ without splint/ with splint mm
1	Smallest value [mm]	0.9	0.7	-0.2	1.2	0.7	-0.5
	ø 30 smallest values [mm]	0.9	0.8	-0.1	1.2	0.8	-0.4
2	Smallest value [mm]	0.8	0.8	0.0	0.8	0.8	0.0
	ø 30 smallest values [mm]	0.8	0.8	0.0	0.8	0.8	0.0
3	Smallest value [mm]	1.1	0.5	-0.6	1.3	0.8	-0.5
	ø 30 smallest values [mm]	1.1	0.6	-0.5	1.3	0.9	-0.4
4	Smallest value [mm]	0.7	0.6	-0.1	0.7	0.6	-0.1
	ø 30 smallest values [mm]	0.7	0.6	-0.1	0.7	0.6	-0.1
5	Smallest value [mm]	0.6	0.0	-0.6	0.8	0.2	-0.6
	ø 30 smallest values [mm]	0.7	0.0	-0.7	0.9	0.3	-0.6
6	Smallest value [mm]	0.7	0.6	-0.1	0.8	0.7	-0.1
	ø 30 smallest values [mm]	0.7	0.7	0.0	0.8	0.7	-0.1
7	Smallest value [mm]	0.8	0.6	-0.2	0.9	0.6	-0.3
	ø 30 smallest values [mm]	0.8	0.6	-0.2	0.9	0.7	-0.2
8	Smallest value [mm]	0.7	0.7	0.0	0.8	0.7	-0.1
	ø 30 smallest values [mm]	0.8	0.7	-0.1	0.8	0.8	0.0
9	Smallest value [mm]	0.0	0.8	0.8	0.5	0.8	0.3
	ø 30 smallest values [mm]	0.0	0.8	0.8	0.6	0.8	0.2
10	Smallest value [mm]	0.8	0.5	-0.3	0.8	0.7	-0.1
	ø 30 smallest values [mm]	0.9	0.6	-0.3	0.9	0.9	0.0
	Min Smallest value [mm]	0.0	0.0	-0.6	0.5	0.2	-0.6
	Min ø 30 smallest values [mm]	0.0	0.0	-0.7	0.6	0.3	-0.6
	X0.25 Smallest value [mm]	0.7	0.5	-0.3	0.8	0.6	-0.5
	X0.25 ø 30 smallest values [mm]	0.7	0.6	-0.3	0.8	0.7	-0.4
	Median Smallest value [mm]	0.8	0.6	-0.1	0.8	0.7	-0.1
	Median ø 30 smallest values [mm]	0.8	0.7	-0.1	0.9	0.8	-0.1
	X0.75 Smallest value [mm]	0.8	0.7	0.0	0.9	0.8	-0.1
	X0.75 ø 30 smallest values [mm]	0.9	0.8	0.0	0.9	0.8	0.0
	Max Smallest value [mm]	1.1	0.8	0.8	1.3	0.8	0.3
	Max ø 30 smallest values [mm]	1.1	0.8	0.8	1.3	0.9	0.2

Table 6. Statistical evaluation of minimum distances: ANOVA for repeated measurements (generated by SPSS™ software) with following factors:

Dtype: single smallest distance or average of 30 smallest distances;
Side: left or right;
Position: maximum intercuspation or protrusion
Structure: distances between condyle and fossa or disc thickness
Splint: without or with Michigan splint

Significance: n.s. non significant; * p<0.05; ** p<0.01; *** p<0.001.

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	
Dtype (value of the smallest distance versus average of the thirty smallest distances)	Sphericity Assumed	.202	1.000	.202	213.440	.000	***
	Greenhouse-Geisser	.202	1.000	.202	213.440	.000	
	Huynh-Feldt	.202	1.000	.202	213.440	.000	
	Lower-bound	.202	1.000	.202	213.440	.000	
Side (left versus right)	Sphericity Assumed	.014	1.000	.014	.042	.841	n.s.
	Greenhouse-Geisser	.014	1.000	.014	.042	.841	
	Huynh-Feldt	.014	1.000	.014	.042	.841	
	Lower-bound	.014	1.000	.014	.042	.841	
Position (MI versus Protrusion)	Sphericity Assumed	2.749	1.000	2.749	12.830	.006	**
	Greenhouse-Geisser	2.749	1.000	2.749	12.830	.006	
	Huynh-Feldt	2.749	1.000	2.749	12.830	.006	
	Lower-bound	2.749	1.000	2.749	12.830	.006	
Structure (disc versus condyle/ fossa)	Sphericity Assumed	2.763	1.000	2.763	27.259	.001	**
	Greenhouse-Geisser	2.763	1.000	2.763	27.259	.001	
	Huynh-Feldt	2.763	1.000	2.763	27.259	.001	
	Lower-bound	2.763	1.000	2.763	27.259	.001	
Splint (without splint versus with splint)	Sphericity Assumed	.411	1.000	.411	3.293	.103	n.s
	Greenhouse-Geisser	.411	1.000	.411	3.293	.103	
	Huynh-Feldt	.411	1.000	.411	3.293	.103	
	Lower-bound	.411	1.000	.411	3.293	.103	

Table 7. Qualitative evaluation of main loading areas of the left disc in a 3×3 matrix. Position of the main loading area without and with splint in maximum intercuspation and maximum protrusion. Direction of the movement vectors from the condition without splint to the condition with splint.

	Position				**Movement vector wosp → sp**	
	MI		**Prot**			
Subject	**wosp**	**sp**	**wosp**	**sp**	**MI**	**Prot**
1	central	central	central	central	ventromedial	medial
2	lateral	central	central	central	medial	ventromedial
3	medial	central	medial	medial	lateral	lateral
			central	lateral		lateral
4	central	central	central	lateral	dorsolateral	ventrolateral
			lateral			ventromedial
5	central	medial	central	medial	medial	medial
6	lateral	ventrolateral	lateral	lateral	ventral	dorsal
7	ventrolateral	ventrolateral	lateral	central	lateral	medial
	dorsomedial	medial			ventral	
8	ventromedial	medial	central	central	lateral	medial
9	central	medial	lateral	central	ventromedial	ventromedial
10	lateral	lateral	lateral	medial	no change	medial
numerical overview						
central	4	4	6	5	1	0
medial	1	4	1	3	2	5
ventromedial	1	0	0	0	2	3
ventral	0	0	0	0	2	0
ventrolateral	1	2	0	0	0	1
lateral	3	1	5	3	3	2
dorsolateral	0	0	0	0	1	0
dorsal	0	0	0	0	0	1
dorsomedial	1	0	0	0	0	0
no change					1	0
medial direction					4	8
lateral direction					4	3
dorsal direction					1	1
ventral direction					4	4

Abbreviations:
MI: maximum intercuspation
Prot: protrusion
wosp: without splint
sp: with splint

Table 7a. Distribution of main loading areas of the left disc in a 3×3 matrix. Position of the main loading area without and with splint in maximum intercuspation (MI) and maximum protrusion (Prot). Movement vectors from the condition without splint (wosp) to the condition with splint in MI and Prot.

		ventral		
	0	0	2	
Medial	4	4	1	lateral
	0	0	0	
		dorsal		

Position MI with splint

		ventral		
	2	2	0	
medial	2	1	3	lateral
	0	0	1	
		dorsal		

Movement vector MI wosp → with splint

		ventral		
	0	0	0	
medial	3	5	3	lateral
	0	0	0	
		dorsal		

Position Prot with splint

		ventral		
	3	0	1	
medial	5	0	2	lateral
	0	1	0	
		dorsal		

Movement vector Prot wosp → with splint

Table 8. Qualitative evaluation of main loading areas of the right disc in a 3×3 matrix. Position of the main loading area without and with splint in maximum intercuspation and maximum protrusion. Direction of movement vectors from the condition without splint to the condition with splint.

Subject	Position				Movement vector wosp → sp	
	MI		Prot			
	wosp	sp	wosp	sp	MI	Prot
1	central	central	central	central	dorsomedial	dorsolateral
2	lateral	central	central	central	medial	lateral
				medial		medial
3	medial	medial	central	lateral	medial	lateral
4	central	lateral	central	lateral	dorsolateral	lateral
			lateral			medial
5	central	lateral	lateral	lateral	dorsolateral	medial
6	ventral	central	central	lateral	dorsal	dorsolateral
7	central	central	central	medial	medial	medial
8	medial	medial	lateral	medial	medial	medial
9	medial	medial	central	central	ventral	dorsomedial
10	central	central	central	medial	no change	medial
numerical overview						
central	5	5	8	3	1	0
medial	3	3	0	4	4	6
ventromedial	0	0	0	0	0	0
ventral	1	0	0	0	1	0
ventrolateral	0	0	0	0	0	0
lateral	1	2	3	4	0	3
dorsolateral	0	0	0	0	2	2
dorsal	0	0	0	0	1	0
dorsomedial	0	0	0	0	1	1
no change					1	0
medial direction					5	7
lateral direction					2	5
dorsal direction					4	3
ventral direction					1	0

Abbreviations:
Subj: subject
MI: maximum intercuspation
Prot: protrusion
wosp: without splint
sp: with splint

Table 8a. Distribution of main loading areas of the right disc in a 3×3 matrix. Position of the main loading area without and with splint in maximum intercuspation (MI) and maximum protrusion (Prot). Movement vectors from the condition without splint (wosp) to the condition with splint in MI and Prot.

	ventral			
lateral	0	0	0	medial
	2	5	3	
	0	0	0	
	dorsal			

Position MI with splint

	ventral			
lateral	0	1	0	medial
	0	1	4	
	2	1	1	
	dorsal			

Movement vector MI wosp → with splint

	ventral			
lateral	0	0	0	medial
	4	3	4	
	0	0	0	
	dorsal			

Position Prot with splint

	ventral			
lateral	0	0	0	medial
	3	0	6	
	2	0	1	
	dorsal			

Movement vector Prot wosp → with splint

Table 9. Explanation of the 3×3 matrix placed over the disc for the qualitative evaluation of main loading areas.

Denomination of the nine cells formed by placing a 3x3 matrix over the disc in a caudodorsal view (left side):

ventromedial	ventral	ventrolateral
medial	central	lateral
dorsomedial	dorsal	dorsolateral

Denomination of the nine cells formed by placing a 3x3 matrix over the disc in a caudodorsal view (right side):

ventrolateral	ventral	ventromedial
lateral	central	medial
dorsolateral	dorsal	dorsomedial

Denomination of the nine cells formed by placing a 3x3 matrix over the disc in a frontocranial view (left side):

dorsomedial	dorsal	dorsolateral
medial	central	lateral
ventromedial	medial	dorsomedial

Denomination of the nine cells formed by placing a 3x3 matrix over the disc in a frontocranial view (right side):

dorsolateral	dorsal	dorsomedial
lateral	central	medial
ventrolateral	ventral	ventromedial

Table 10. Qualitative evaluation of the main loading areas of the left condyle in protrusion in a 3×3 matrix in frontocranial view. Position of the main loading areas without and with splint in maximum protrusion. Direction of movement vectors from the condition without splint to the condition with splint.

	Position of the main loading area		**Movement vector wosp → sp**
Subject:	**Without splint**	**With splint**	
1	lateral	lateral	dorsomedial
2	dorsal	dorsomedial	medial
3	dorsal	dorsolateral	dorsolateral
		dorsomedial	dorsomedial
4	dorsal	dorsal	dorsolateral
5	medial	medial	medial
6	lateral	dorsolateral	dorsal
7	medial	dorsal	dorsolateral
8	dorsal	dorsal	dorsal
9	dorsolateral	dorsomedial	medial
10	central	medial	medial
Numerical overview			
central	1	0	0
medial	2	2	4
ventromedial	0	0	0
ventral	0	0	0
ventrolateral	0	0	0
lateral	2	1	0
dorsolateral	1	2	3
dorsal	4	3	2
dorsomedial	0	3	2
no change			0
medial direction			6
lateral direction			3
dorsal direction			7
ventral direction			0

Abbreviations:
wosp: without splint
sp: with splint

Table 11. Qualitative evaluation of the main loading areas of the right condyle in protrusion in a 3×3 matrix in frontocranial view. Position of the main loading areas without and with splint in maximum protrusion. Direction of movement vectors from the condition without splint to the condition with splint.

	Position of the main loading area		**Movement vector wosp → sp**
Subject:	**Without splint**	**With splint**	
1	lateral	dorsal	dorsomedial
2	dorsal	dorsal	lateral
3	dorsal	dorsolateral	dorsolateral
4	dorsolateral	dorsal	medial
5	dorsolateral	dorsolateral	medial
6	dorsal	dorsolateral	lateral
7	dorsomedial	dorsomedial	no change
8	dorsolateral	lateral	ventral
9	central	dorsal	dorsomedial
10	lateral	lateral	no change
Numerical overview			
central	1	0	2
medial	0	0	2
ventromedial	1	0	0
ventral	0	0	1
ventrolateral	0	0	0
lateral	2	2	2
dorsolateral	3	3	1
dorsal	3	4	0
dorsomedial	0	1	2

no change	2
medial direction	4
lateral direction	3
dorsal direction	3
ventral direction	1

Abbreviations:
wosp: without splint
sp: with splint

Table 12. Mean intensity of the MR signal of the discs.

Subject		mean	deviation	rms	mean TMJ
1					
	MI wosp left	265.107	116.207	289.450	**453**
	MI sp left	709.671	305.627	772.663	
	Prot wosp left	436.832	208.907	484.203	
Disc left	Prot sp left	405.981	230.588	466.880	
	MI wosp right	345.473	151.850	377.361	**509**
	MI sp right	854.492	365.884	929.507	
	Prot wosp right	453.527	212.873	500.987	
Disc right	Prot sp right	385.270	181.216	425.749	
2					
	MI wosp left	131.817	56.034	143.228	**137**
	MI sp left	132.227	60.486	145.401	
	Prot wosp left	149.220	77.525	168.151	
Disc left	Prot sp left	135.482	64.966	150.248	
	MI wosp right	164.358	63.075	176.042	**159**
	MI sp right	173.261	74.297	188.514	
	Prot wosp right	155.071	84.695	176.686	
Disc right	Prot sp right	145.561	75.762	164.091	
3					
	MI wosp left	144.372	57.880	155.539	**152**
	MI sp left	144.197	62.767	157.262	
	Prot wosp left	163.262	69.771	177.542	
Disc left	Prot sp left	156.034	60.889	167.491	
	MI wosp right	152.667	52.700	161.504	**154**
	MI sp right	154.397	54.952	163.881	
	Prot wosp right	157.342	66.344	170.755	
Disc right	Prot sp right	154.238	71.157	169.857	
4					
	MI wosp left	116.233	55.621	128.851	**118**
	MI sp left	127.509	64.421	142.852	
	Prot wosp left	108.474	58.450	123.214	
Disc left	Prot sp left	120.240	66.886	137.585	
	MI wosp right	107.457	53.903	120.214	**131**
	MI sp right	119.107	64.426	135.409	
	Prot wosp right	148.058	91.858	174.232	
Disc right	Prot sp right	149.570	119.001	191.121	
5					
	MI wosp left	121.905	57.420	134.747	**133**
	MI sp left	122.375	54.356	133.900	
	Prot wosp left	146.832	80.581	167.485	
Disc left	Prot sp left	140.680	87.370	165.597	
	MI wosp right	145.658	73.678	163.224	**155**
	MI sp right	149.763	73.347	166.753	
	Prot wosp right	150.192	75.883	168.269	
Disc right	Prot sp right	174.311	101.967	201.937	

6					
Disc left	MI wosp left	148.075	79.143	167.892	**204**
	MI sp left	176.115	97.722	201.403	
	Prot wosp left	259.755	125.241	288.365	
	Prot sp left	231.267	113.875	257.778	
Disc right	MI wosp right	153.487	68.972	168.267	**207**
	MI sp right	186.942	89.544	207.275	
	Prot wosp right	256.634	112.206	280.087	
	Prot sp right	231.756	116.484	259.377	
7					
Disc left	MI wosp left	138.225	69.452	154.686	**149**
	MI sp left	137.899	63.465	151.797	
	Prot wosp left	189.365	97.483	212.977	
	Prot sp left	131.383	77.930	152.751	
Disc right	MI wosp right	141.151	66.016	155.818	**170**
	MI sp right	145.153	62.260	157.935	
	Prot wosp right	220.882	147.277	265.468	
	Prot sp right	172.850	121.766	211.423	
8					
Disc left	MI wosp left	92.148	48.039	103.913	**110**
	MI sp left	85.056	46.569	96.965	
	Prot wosp left	123.122	63.298	138.437	
	Prot sp left	140.545	73.496	158.598	
Disc right	MI wosp right	71.892	33.632	79.366	**86**
	MI sp right	78.624	34.997	86.058	
	Prot wosp right	95.339	51.562	108.387	
	Prot sp right	97.002	46.590	107.608	
9					
Disc left	MI wosp left	131.450	69.933	148.844	**175**
	MI sp left	136.332	73.661	154.954	
	Prot wosp left	250.843	186.052	312.299	
	Prot sp left	183.820	112.854	215.692	
Disc right	MI wosp right	133.905	67.504	149.954	**160**
	MI sp right	139.903	78.817	160.572	
	Prot wosp right	188.887	124.274	226.096	
	Prot sp right	176.483	105.896	198.359	
10					
Disc left	MI wosp left	151.942	66.063	165.678	**143**
	MI sp left	126.653	56.436	138.654	
	Prot wosp left	135.743	61.156	148.880	
	Prot sp left	156.560	77.484	174.682	
Disc right	MI wosp right	159.378	68.881	173.621	**144**
	MI sp right	146.319	62.962	159.286	
	Prot wosp right	127.115	59.863	140.501	
	Prot sp right	143.076	70.565	159.525	

Abbreviations:
MI: maximum intercuspation
Prot: protrusion
wosp: without splint
sp: with splint

Table 13. Statistical evaluation of mean intensity of the MR signal of the discs: ANOVA for repeated measurements (generated by SPSS™ software) with following factors:

Side: left or right;
Position: maximum intercuspation or protrusion
Splint: without or with Michigan splint

Significance: n.s. non significant; * p<0.05; ** p<0.01; *** p<0.001.

Tests of Within-Subjects Effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	
Side	Sphericity Assumed	2018.071	1.000	2018.071	2.016	.189	n.s.
(left versus right)	Greenhouse-Geisser	2018.071	1.000	2018.071	2.016	.189	
	Huynh-Feldt	2018.071	1.000	2018.071	2.016	.189	
	Lower-bound	2018.071	1.000	2018.071	2.016	.189	
Position	Sphericity Assumed	2951.344	1.000	2951.344	.488	.502	n.s.
(MI versus Prot)	Greenhouse-Geisser	2951.344	1.000	2951.344	.488	.502	
	Huynh-Feldt	2951.344	1.000	2951.344	.488	.502	
	Lower-bound	2951.344	1.000	2951.344	.488	.502	
Splint	Sphericity Assumed	6936.118	1.000	6936.118	.721	.418	n.s.
(without splint	Greenhouse-Geisser	6936.118	1.000	6936.118	.721	.418	
versus with splint)	Huynh-Feldt	6936.118	1.000	6936.118	.721	.418	
	Lower-bound	6936.118	1.000	6936.118	.721	.418	

Table 14. Distance between the most cranial condylar point and the most caudal point of the fossa in protrusion on the left and right side in the situations without and with Michigan splint.

	left			right		
Subject	**Position**	**Distance**	**Difference**	**Position**	**Distance**	**Difference**
1	Prot wosp	7.02mm	2.17mm	Prot wosp	6.60mm	3.72mm
	Prot sp	4.85mm		Prot sp	2.88mm	
2	Prot wosp	3.71mm	4.79mm	Prot wosp	3.59mm	2.09mm
	Prot sp	-1.08mm		Prot sp	1.50mm	
3	Prot wosp	4.45mm	2.07mm	Prot wosp	4.62mm	2.90mm
	Prot sp	2.38mm		Prot sp	1.72mm	
4	Prot wosp	4.93mm	2.94mm	Prot wosp	4.86mm	3.17mm
	Prot sp	1.99mm		Prot sp	1.69mm	
5	Prot wosp	1.46mm	-0.05mm	Prot wosp	5.58mm	1.86mm
	Prot sp	1.51mm		Prot sp	3.72mm	
6	Prot wosp	4.82mm	2.80mm	Prot wosp	2.88mm	-0.21mm
	Prot sp	2.02mm		Prot sp	3.09mm	
7	Prot wosp	6.09mm	3.38mm	Prot wosp	2.21mm	3.38mm
	Prot sp	2.71mm		Prot sp	-1.17mm	
8	Prot wosp	2.39mm	0.99mm	Prot wosp	5.50mm	3.36mm
	Prot sp	1.40mm		Prot sp	2.14mm	
9	Prot wosp	3.58mm	4.88mm	Prot wosp	4.61mm	5.64mm
	Prot sp	-1.30mm		Prot sp	-1.03mm	
10	Prot wosp	7.67mm	2.51mm	Prot wosp	7.36mm	2.81mm
	Prot sp	5.16mm		Prot sp	4.55mm	
Mean deviation			**2.66mm**			**2.87mm**

Abbreviations:
Prot: protrusion
wosp: without splint
sp: with splint

Table 14a. Statistical evaluation of Table 14. Distance between the most cranial condylar point and the most caudal point of the fossa. X0.25 and X0.75: 25th and 75th percentiles.

Overview left TMJs:

	Without splint	Splint	Difference
Smallest value	1.46mm	-1.30mm	-0.05mm
X0.25	3.58mm	1.40mm	2.07mm
Median	4.64mm	2.01mm	2.66mm
X0.75	6.09mm	2.71mm	3.38mm
Biggest value	7.67mm	5.16mm	4.88mm

Overview right TMJs:

	Without splint	Splint	Difference
Smallest value	2.21mm	-1.17mm	-0.21mm
X0.25	3.59mm	1.50mm	2.09mm
Median	4.74mm	1.93mm	3.04mm
X0.75	5.58mm	3.09mm	3.38mm
Biggest value	7.36mm	4.55mm	5.64mm

Table 15. Statistical evaluation of distance between the most cranial condylar point and the most caudal point of the fossa: ANOVA for repeated measurements (generated by SPSS™ software) with following factors:

Side: left or right;
Splint: without or with Michigan splint

Significance: n.s. non significant; * p<0.05; ** p<0.01; *** p<0.001.

Multivariate Tests[b]

Effect		Value	F	Hypothesis df	Error df	Sig.	
Side (left versus right)	Pillai's Trace	.001	.009[a]	1.000	9.000	.927	n.s.
	Wilks' Lambda	.999	.009[a]	1.000	9.000	.927	
	Hotelling's Trace	.001	.009[a]	1.000	9.000	.927	
	Roy's Largest Root	.001	.009[a]	1.000	9.000	.927	
Splint (without splint versus with splint)	Pillai's Trace	.852	51.808[a]	1.000	9.000	.000	***
	Wilks' Lambda	.148	51.808[a]	1.000	9.000	.000	
	Hotelling's Trace	5.756	51.808[a]	1.000	9.000	.000	
	Roy's Largest Root	5.756	51.808[a]	1.000	9.000	.000	

10. Figures

Figure 1. Fabrication of a Michigan splint. Casts mounted arbitrarily in a Gerber articulator and determination of the common dental equator.

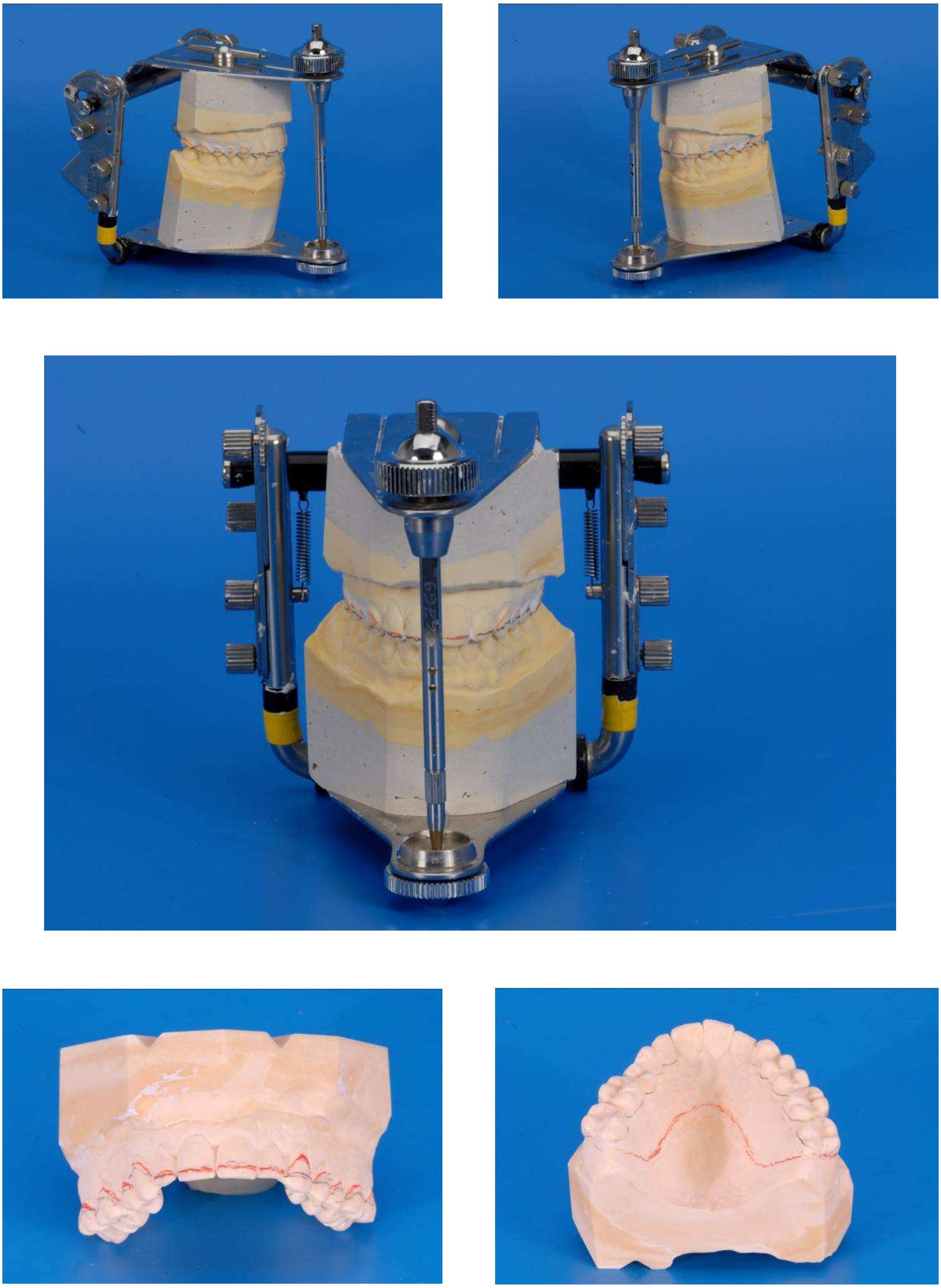


Figure 2. Fabrication of a Michigan Splint in wax.

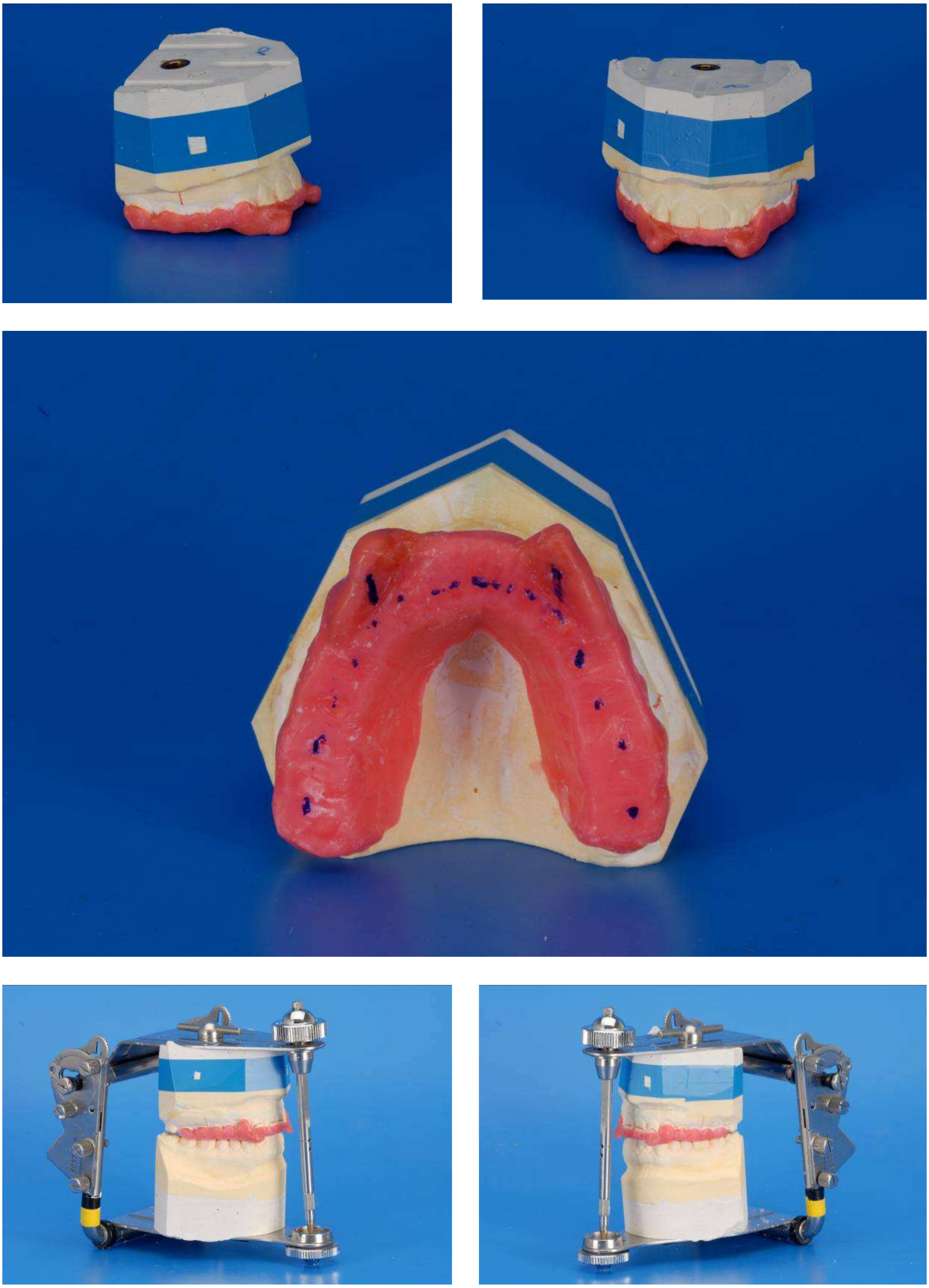


Figure 3. Fabrication of a Michigan splint. Completed Michigan splint.

Figure 4. Inserted Michigan splint.

Figure 5. Silicone index to hold the mandible in maximum protrusion. Top without splint, bottom with inserted Michigan splint.

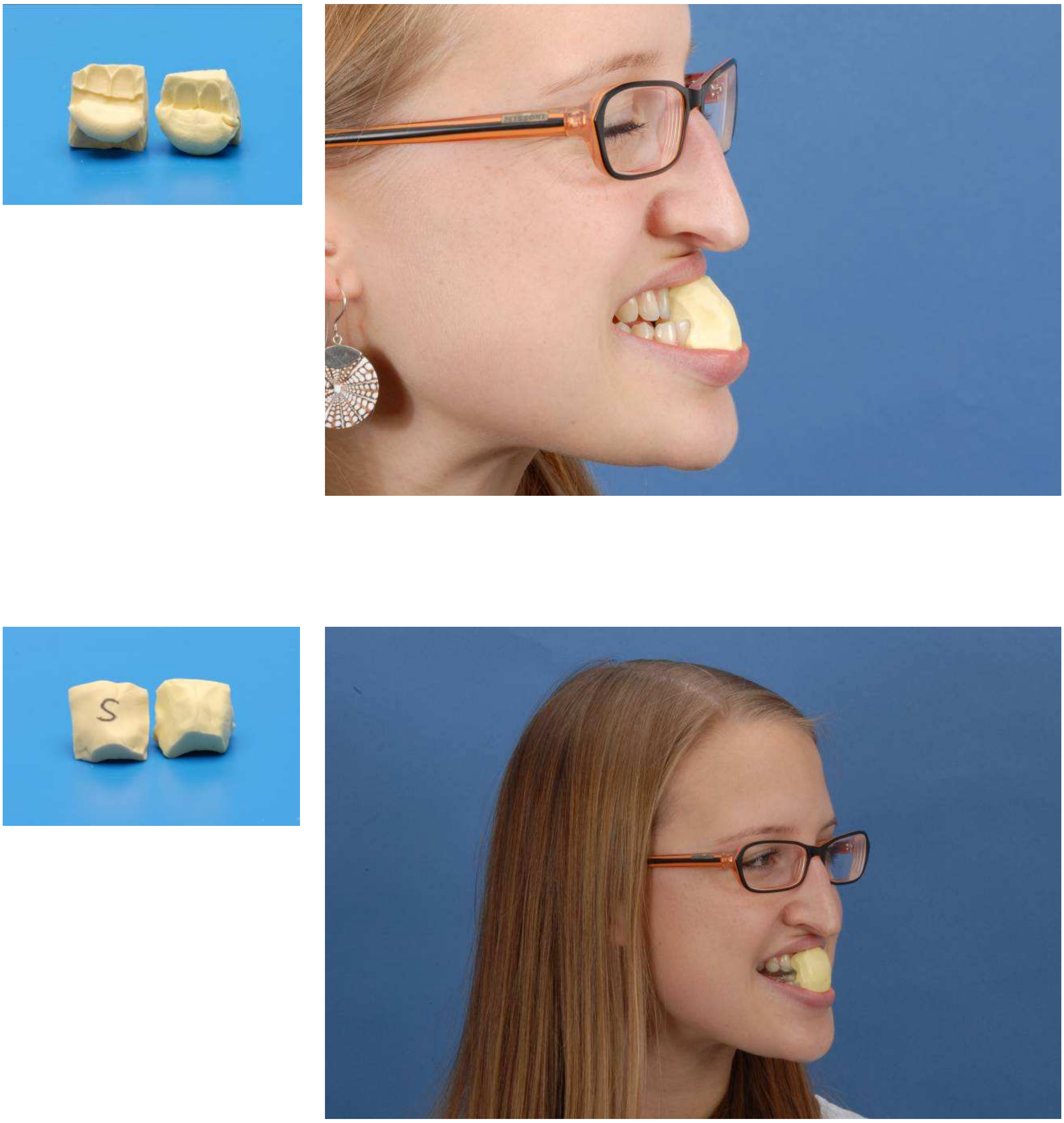


Figure 6. Graphic representation of the minimum distances between condyle and fossa. The minimum distance increases from red, yellow, green to blue and dark blue.

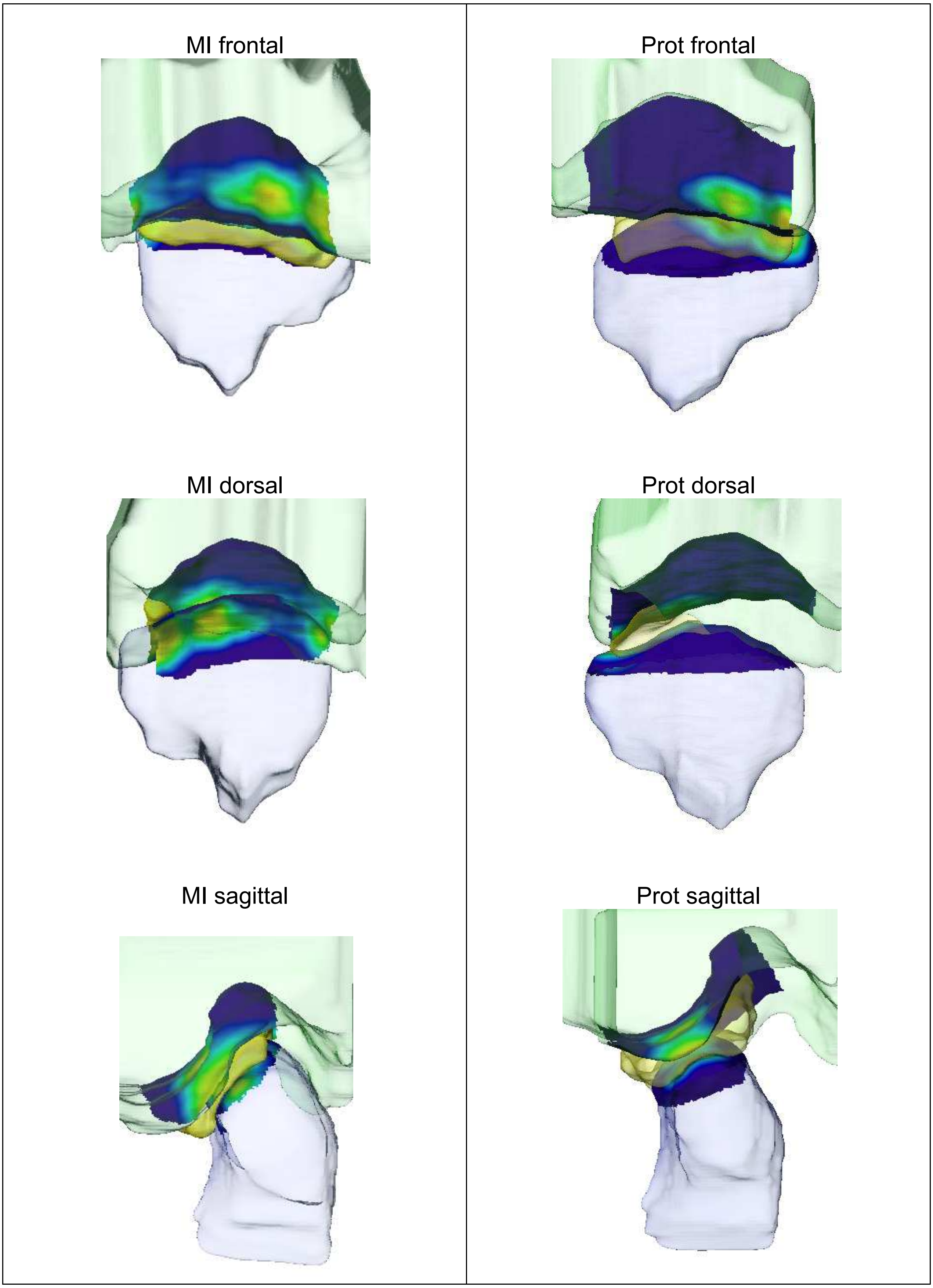


Figure 7. Graphic representation of the minimum disc thickness. The minimum thickness increases from red, yellow, green to blue and dark blue.

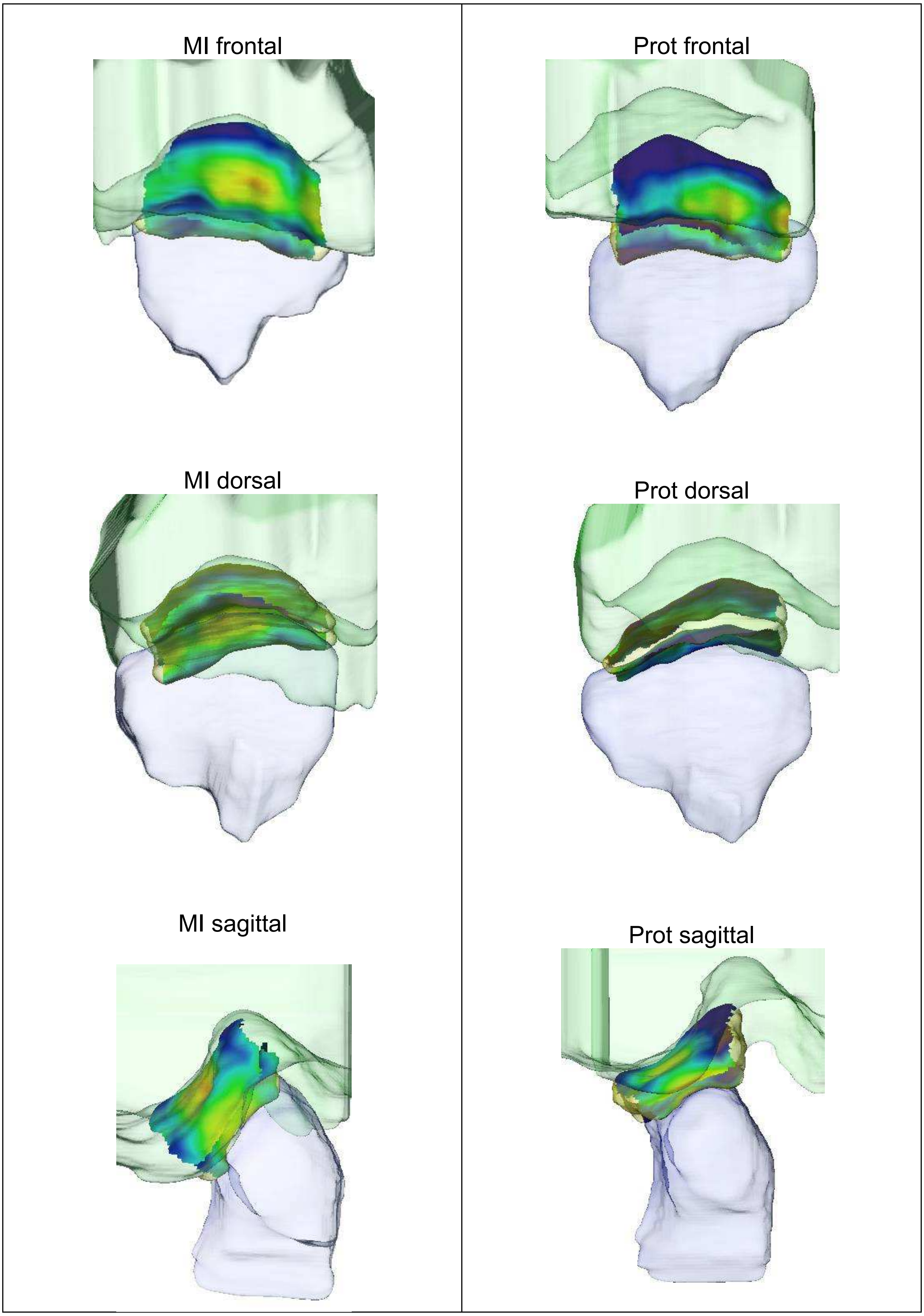
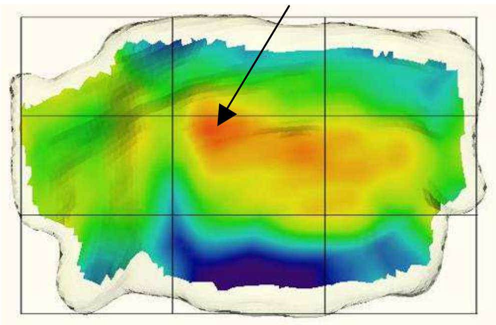
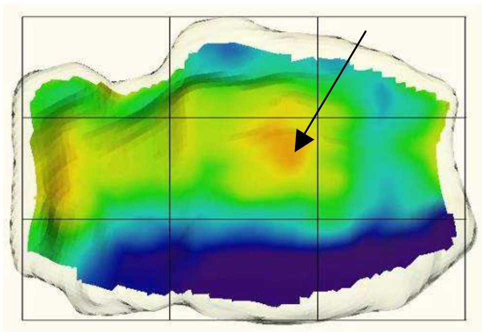


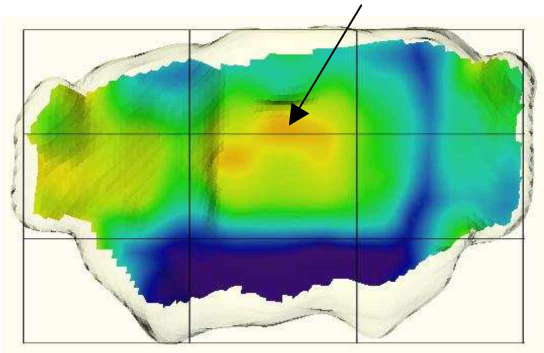
Figure 8. Caudodorsal view of the disc, the arrows point to the main loading areas. The thickness of the disc increases from red to yellow, green on to blue and dark blue. Also visible is the 3×3 matrix placed over the disc.



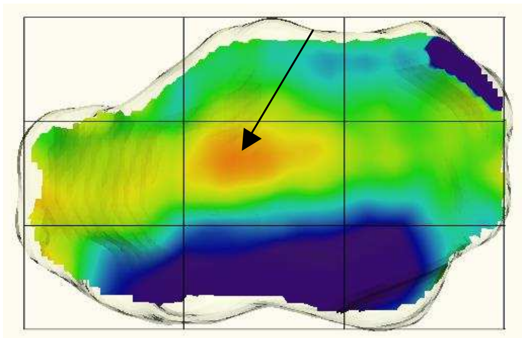
MI without splint



MI with splint



Prot without splint



Prot with splint

Figure 9. Three examples of condyle-related stress-fields. The arrows point to the main loading area of the condyle. Red: main loading area; dark blue least loaded areas.

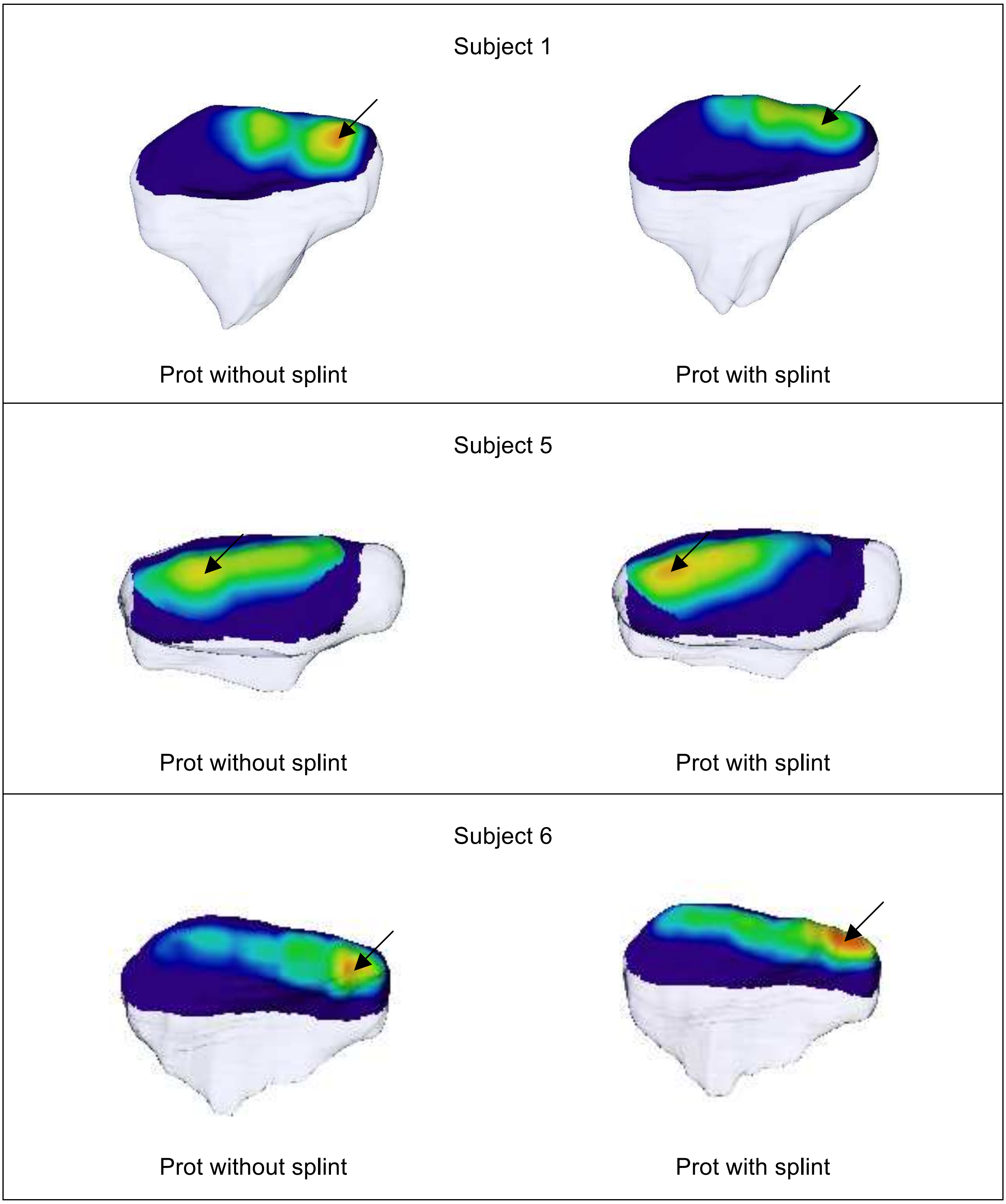


Figure 10. Sectional images from the left fossa of subject #10 in sagittal and coronal view. As already mentioned in the discussion, the shape of the fossa slope is more strongly curved medially and laterally, so that the distance between condyle and fossa decreases laterally and/or medially with increasing protrusion.

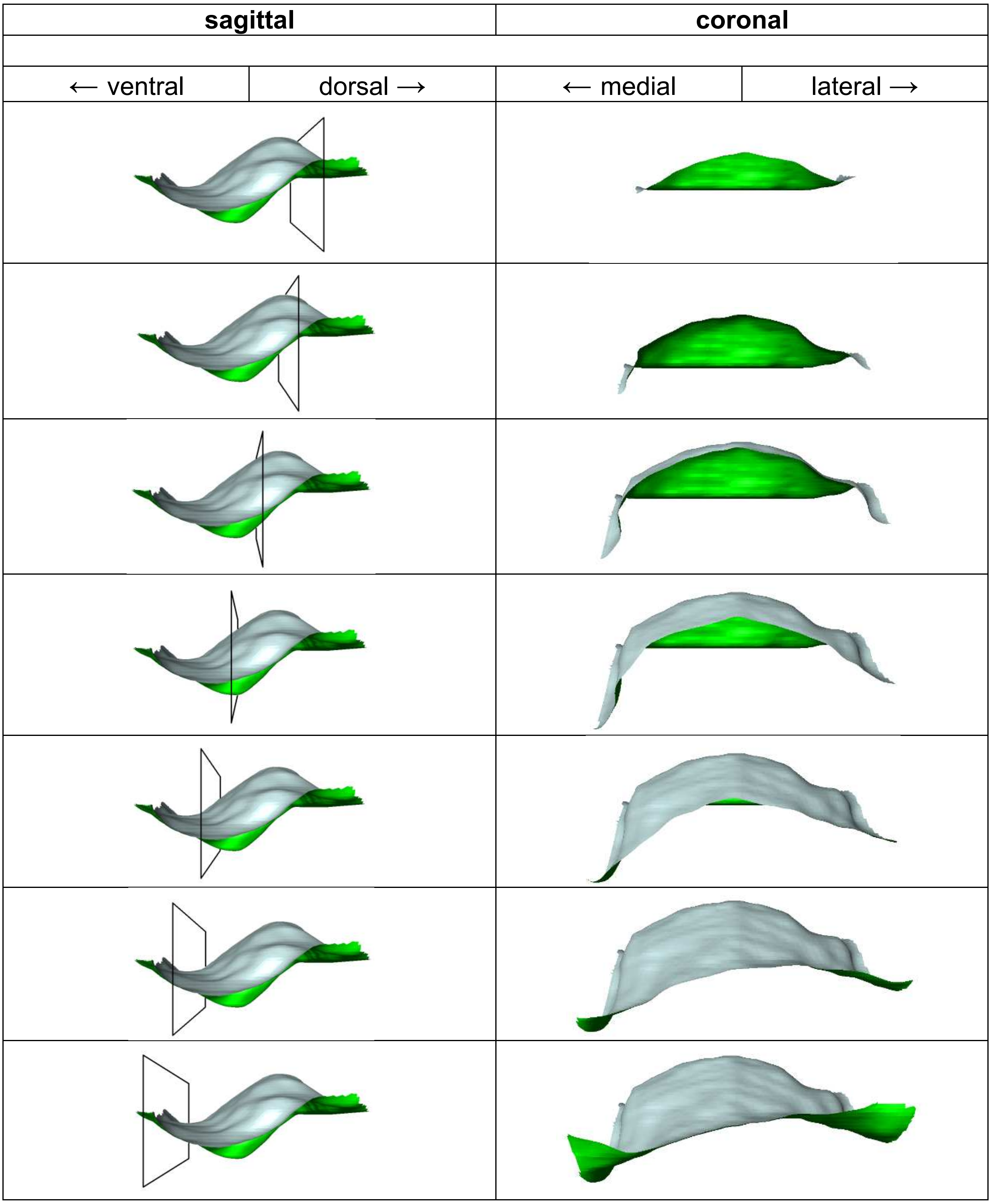
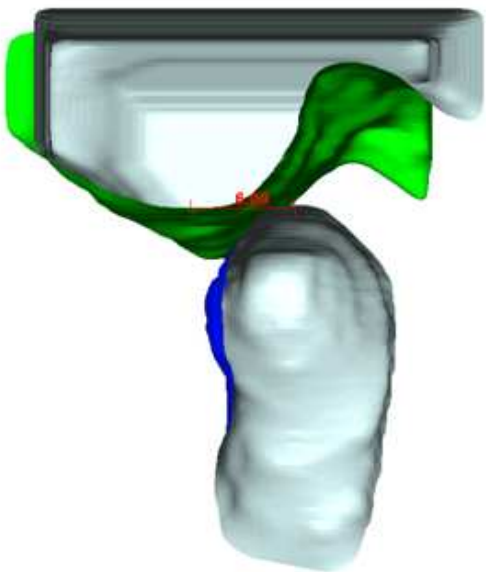


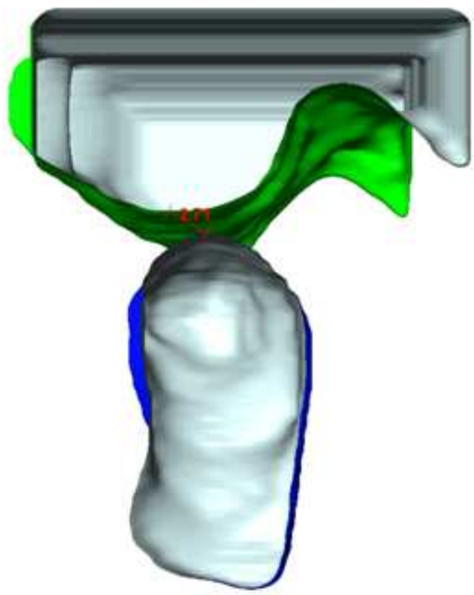
Figure 11. Comparison of the condyle-fossa distance in protrusion without and with Michigan splint. The distance between the most cranial point of the condyle and the most caudal point of the fossa was measured.

Subject 7 right TMJ

Prot without splint

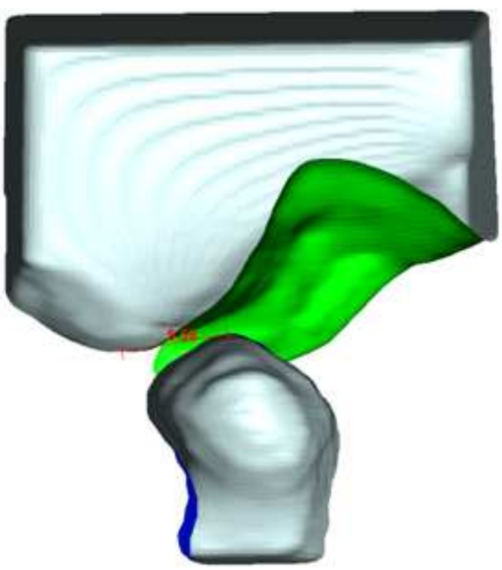


Prot with splint



Subject 5 right TMJ

Prot without splint



Prot with splint